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Distributed photovoltaic generation and energy storage systems: A review

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ABSTRACT

Currently, in the field of operation and planning of electrical power systems, a new challenge is growing which includes with the increase in the level of distributed generation from new energy sources, especially renewable sources. The question of load redistribution for better energetic usage is of vital importance since these new renewable energy sources are often intermittent. Therefore, new systems must be proposed which ally energy storage with renewable energy generators for reestablishment of grid reliability. This work presents a review of energy storage and redistribution associated with photovoltaic energy, proposing a distributed micro-generation complex connected to the electrical power grid using energy storage systems, with an emphasis placed on the use of NaS batteries. These systems aim to improve the load factor, considering supply side management, and the offer of backup energy, in the case of demand side management.

Contents

1. Introduction

The world is currently facing a double threat in the energy sector, including the absence of a secure and adequate energy source at accessible prices and environmental damages caused by excessive energy consumption and the use of high polluting energy sources, such as petroleum and coal. Rapid increase in energy prices and recent geopolitical events serves as reminder of the importance of energy at accessible prices has on economic growth and human development, as well as vulnerability of the global energetic system to shortages. Protection of energy sources is often found at the top of the international political agenda [1,2]. However, the current standard energy sources are accompanied by threats of grave and irreversible damage to the environment, including world climate alterations. Conciliation of the energetic security and environmental protection objectives require a strong intervention and must be coordinated in part by the state, together with the help of society [1].

Brazil possesses one of the most centralized energy-infrastructures in the world, in which around 90% of electrical generation capacity is accounted for by hydroelectric stations, located in remote areas with vast transmission networks. Therefore, large problems faced in Brazil have been in the mobilization of investments for infrastructure and the resolution of environmental questions for the construction of large dams and transmission lines [1,3,4].

These factors point to a change in the Brazilian electrical energy panorama in the near future by means of increasing distributed generation. The projection is for an alteration of the current structure, highly centralized with large capacity generators, for a

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new decentralized infrastructure with the insertion of small and medium capacity generators [4,5]. This tendency requires the reengineering of electric power grids and insertion of distributed energy resources, indicating that electrical transmission and distribution systems must pursue the following objectives [6]:

- Supply the growing load demand and reinforce grid strength with minimal increases of the transmission system;
- Enable and expand the use of renewable energy sources, such as wind and photovoltaic systems;
- Increase energetic efficiency and reduce pollution and greenhouse gas emissions and;
- Expand the local reliability level to guarantee energy quality required by the consumers.

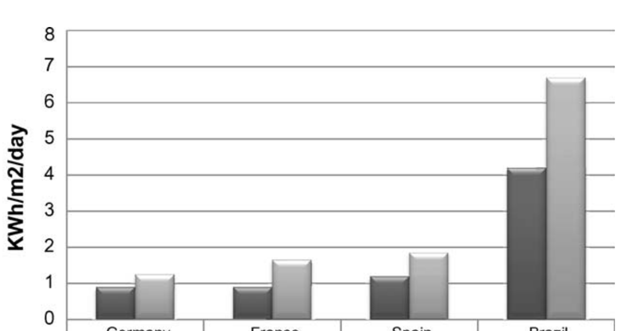
The main characteristics of distributed generation in contrast with centralized generation are: (i) size (distributed generation signifies many small scale generation units while centralized generation includes few large scale generation units), (ii) scattered location and (iii) modular sizing (distributed generation permits easy expansion due to its modularity) [6–8].

In function of their characteristics, photovoltaic systems are adequate to be used for electrical distributed generation. It is a modular technology which permits installation conforming to demand, space availability and financial resources. Photovoltaic systems do not emit any pollutants during electricity generation and can therefore be installed in residential or commercial sectors with large populations without offering health risks. Buildings are responsible for approximately 40% of the total world annual energy consumption; and most of this energy is used for lighting, heating, and air conditioning [9]. Moreover, photovoltaic systems can provide electricity to urban centers without increasing to the already grave environmental problems often encountered in these areas [10–12].

One of the greatest challenges to the insertion of distributed generation, especially to the use of photovoltaic technology, is the utilization of its benefits without losses in reliability and with satisfactory operation of electrical power systems. Specific options for meeting these proposals were discussed with a focus on distributed energy storage systems. The main objective of this work was therefore to review distributed photovoltaic generation and energy storage systems aiming to increase overall reliability and functionality of the system.

2. Photovoltaic distributed generation

In Brazil, annual global solar incident radiation values are greater than those of the countries of the European Union (EU),



	Germany	France	Spain	Brazil
Minimum	0.9	0.9	1.2	4.2
Maximum	1.25	1.65	1.85	6.7

Fig. 1. Comparison of the average daily solar global incident radiation between countries with photovoltaic subventions and Brazil [13].

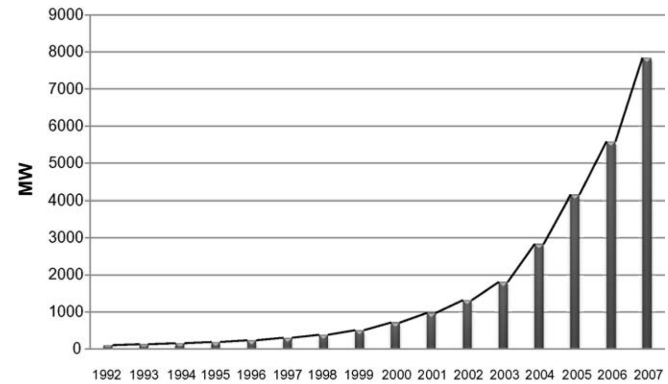


Fig. 2. Cumulative growth of installed photovoltaic potential (isolated and connected to the electrical power system) in countries studied[1] by the IEA-PVPS project. Source: [20].

including Germany, France and Spain (Fig. 1). These countries of the EU rely on governmental subsidies for the implementation of renewable energy projects and many of these projects are in operation, especially in Spain and Germany [13,14].

The photovoltaic effect is one of the possible forms of solar energy conversion into electricity which occurs in devices known as *photovoltaic cells*. Solar energy conversion occurring in these photovoltaic cells consists of two essential stages. First, absorption of light (photons) generates an electron–hole pair, causing separation of electron cohesion in the valence band. Therefore the electron and hole are separated by the equipment structure, electrons on the negative terminal and holes on the positive terminal, generating a voltage difference, hence, electricity [15]. When photovoltaic cells are grouped together in panels, they give origin to the photovoltaic generator, or photovoltaic module, utilized in solar generation systems.

Distributed photovoltaic systems connected to the grid can be installed to furnish energy to a specific consumer or directly to the grid, increasing reliability of the systems. According to Hoff et al. [11], the benefits of distributed solar generation include practically generated energy, increase in generation capacity, avoided costs of transmission and distribution, reduction in losses in transformers and transmission lines, possibility to control reactive power and the fact that they are environmentally friendly. Environmental benefits can be measured in terms of greenhouse gas emissions. A 5 MW PV power plant operating in Saudi Arabia eliminated the emission of roughly 914 t of greenhouse gases, considering its substitution of a coal fired power plant of the same size [16]. Carbon emissions from photovoltaic cells are the result of electricity use during manufacturing [17]. Celik et al. [18] documented that, with the conservative European average electricity mix, energy payback time (EPBT) is 2–6 years and CO_2 payback time is 4–6 years for the photovoltaic system. The decreasing prices of photovoltaic systems have been driven by (1) solar cell efficiency improvements; (2) manufacturing-technology improvements; and (3) economies of scale [19].

Photovoltaic systems, especially those connected to the grid, have shown strong growth in the last five years, principally in developed countries (Fig. 2). In these countries during 2006, roughly 1.5 GW of photovoltaic capacity was installed, representing a 34% increase in relation to the previous year. In 2007 a 40% increase in photovoltaic capacity was installed, reaching a total installed capacity of 7.8 GW [20].

[1] Countries of the IEA PVPS programme: Australia, Austria, Canada, Denmark, France, Germany, Israel, Italy, Japan, Korea, Mexico, Holland, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom and United States of America.

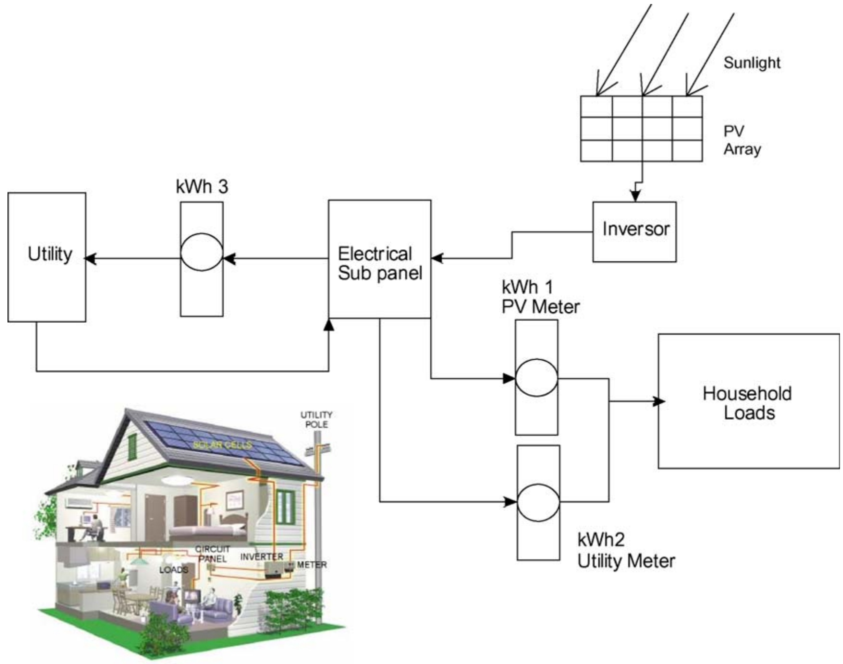


Fig. 3. Photovoltaic system connected to the grid.*Source*: [21].

Fig. 3 presents a schematic diagram of a photovoltaic system connected to an electrical distribution grid; in this case the system attends only one consumer, but can be expanded to attend a group of consumers. Power meter 1 (kWh1) measures the energy generated by the photovoltaic system to meet its own load demand; power meter 2 (kWh2) measures the energy generated by the solar system to be injected to the electrical grid; and meter 3 (kWh3) measures the energy received by the grid, representing power flows [21].

When considering photovoltaic systems connected to the power grid, some basic orientations serve as a basis to add value to its implementation. Fig. 4 depicts certain situations and benefits to the electrical energy system when implementing photovoltaic systems [22]

3. Energy storage systems

The basis of an energy system is the capacity of this system to generate sufficient energy to attend demand at accessible prices and to provide clean, safe and reliable electricity. Therefore, electrical energy storage has always been a challenge since various electrical energy generation technologies are subject to non-linear supply based on factors such as season (hydroelectricity and wind) and intermittence (solar), without considering load changes.

Energy storage technologies cover a wide spectrum of power system applications (Fig. 5). These applications require energy discharges ranging from fractions of a second in high power applications to hours in high energy applications [23,24].

Currently there exist various technologies for the application of energy storage systems. Nourai [23], compared different technologies for energy storage applications, such as super-capacitors (electrochemical capacitors), flow batteries (ZnBr, VRB and PSB), sodium–sulfur batteries (NaS), lithium–ion batteries (Li–ion), nickel–cadmium batteries (Ni–Cd), lead–acid batteries, metal–air batteries, pumped hydro, compressed air energy storage (CAES) and flywheels. Fig. 6 shows a comparison between

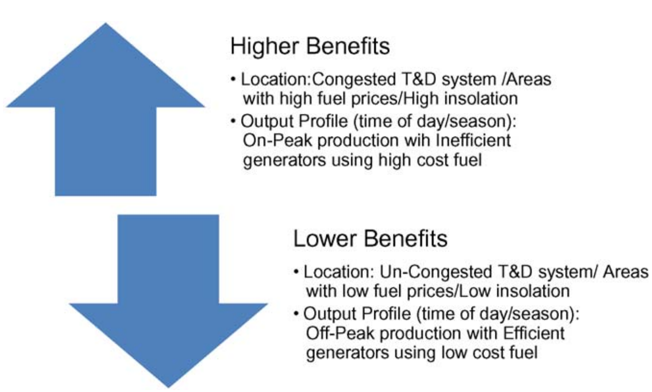


Fig. 4. Guidelines to assess economic viability of photovoltaic system implementation.*Source*: [22].

POWER QUALITY AND UNINTERRUPTIBLE POWER SUPPLY APPLICATIONS		ENERGY MANAGEMENT APPLICATIONS
Extremely Fast Run Time (seconds)	Fast Run Time (minutes)	Slow Run Time (hours)
Flicker Compensation	Spinning Reserve	Load Leveling
	Uninterruptible Power Supply	Peak Shaving
Voltage Sags Correction	Black Start	Energy Market (Arbitrage)
		Island Operation
		Integration of Renewables Sources
		Energy Trading

Fig. 5. Classification of energy storage applications in electric power systems.*Source*: [24].

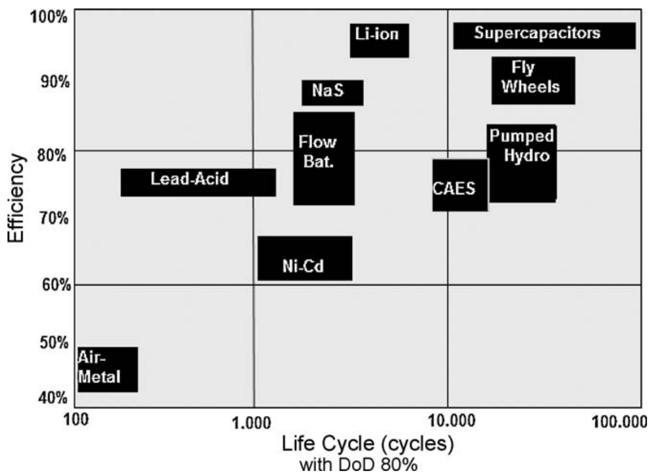


Fig. 6. Efficiency and reliability in discharge cycles for diverse energy storage technologies.*Source*: [23].

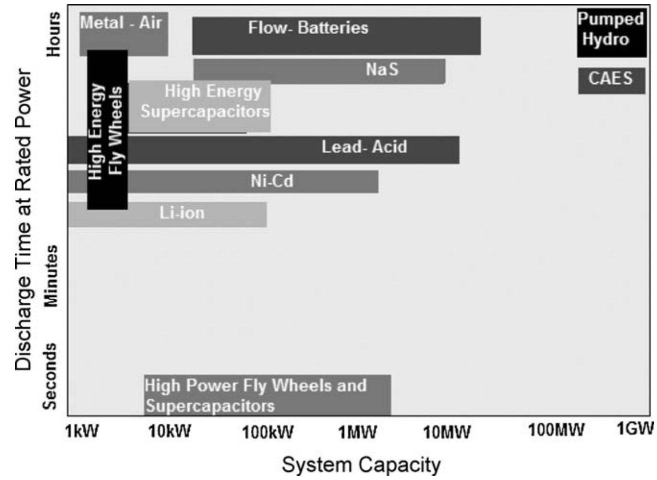


Fig. 7. Application of energy storage systems in terms of discharge time and rated power.*Source*: [23].

diverse energy storage technologies in terms of efficiency and durability in charge–discharge cycles with an 80% depth of discharge [23].

Energy storage systems for high power applications which includes maintenance of energy quality and continual supply of demand requires storage technologies such as supercapacitors, flywheels and others which are utilized in fractions of a second to guarantee reliability of the system. In high energy applications which includes energy management (supply and demand side management (SSM/DMS), balancing of the load curves and peak-shaving) storage technologies which utilize daily charge–discharge cycles to insure economic gains, such as fuel cells and sodium–sulfur (NaS) batteries are better suited [23]. Fig. 7 shows applications of energy storage systems in accordance with discharge time and rated power.

Considering that distributed generation systems are often of small scale and require energy storage of only a few MW for a few hours in different locations, as in the case of photovoltaic generation, sodium–sulfur (NaS) batteries present one of the best options for energy management, including peak-shaving and load curve balancing. Its greatest disadvantage is its cost, which is still quite high but tends to decrease as a function of scale [23,25]. These batteries can be effectively applied for load side and supply side management.

Sodium–sulfur (NaS) batteries are high capacity battery systems developed for application in electrical power systems. These batteries consist of a molten sulfur positive electrode and a molten sodium negative electrode separated by a sodium beta-alumina ceramic electrolyte. The electrolyte permits that only positive sodium ions pass to combine with sodium for the formation of sodium polysulfide [26]. Eq. (1) shows this chemical reaction.

$$2Na + 4S = Na_2S_4 \tag{1}$$

During the discharge process, positive sodium ions (Na+) flow through the electrolyte and electrons pass through an external circuit generating a voltage of roughly 2 V. This process is reversible; and by using the charge, sodium ions are liberated from the sodium polysulfide and return through the electrolyte to recombine with the sodium element. This process is portrayed in Fig. 8 [27].

The NaS battery is hermetically sealed and functions at approximately 300 °C. At this temperature the battery operates normally and the active materials react rapidly since the electrodes are in the liquid state, the electrolyte is in the solid state and internal resistance is low. Due to reversibility of the charging and discharging processes, this type of battery can be used continuously [26].

Characteristics of NaS commercial battery modules include: (i) expected duration of 15 years considering 2500 cycles (charge and discharge) for a 100% depth of discharge (DOD), 4500 cycles for a 90% DOD or 6500 cycles for a 65% DOD; (ii) output voltage (CC) of 64 or 128 V for peak-shaving application modules and 640 V for energy quality application modules (Fig. 9 presents one application example); (iii) power of 50 kW; (iv) energy of 430 kWJ for application in peak-shaving and 360 kWh for application in energy quality; (v) rapid response time, complete discharge in 1 ms if necessary; (vi) high energy density, three to five times that of a

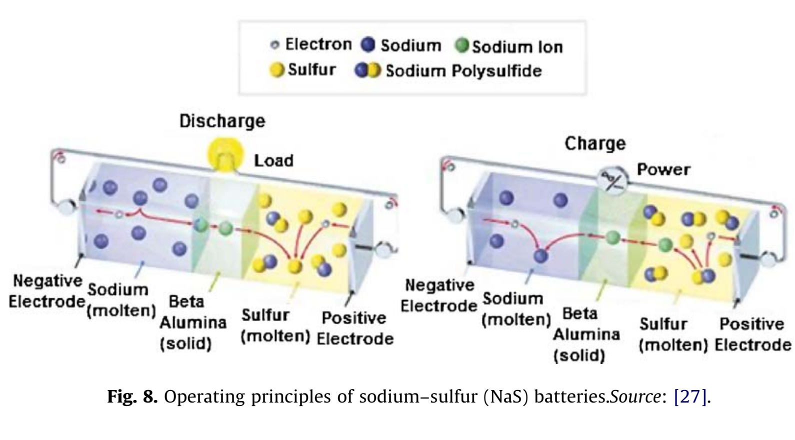


Fig. 8. Operating principles of sodium–sulfur (NaS) batteries.*Source*: [27].

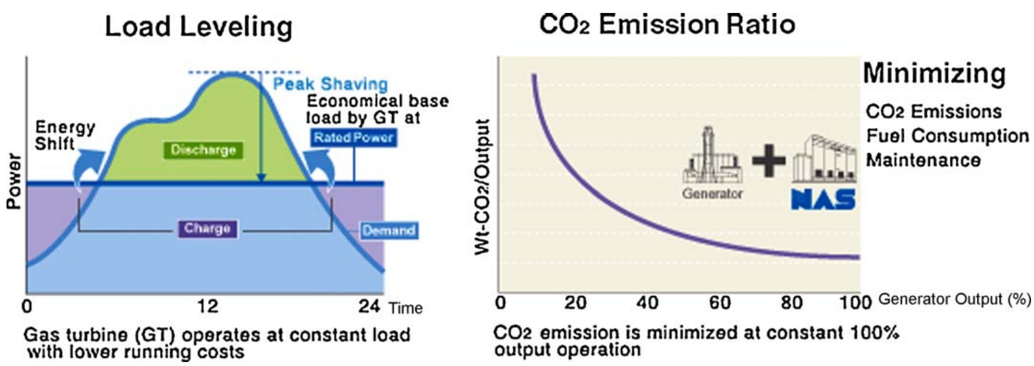


Fig. 9. Application of sodium-sulfur batteries in conjunction with thermoelectric generation for peak-shaving.*Source*: [27].

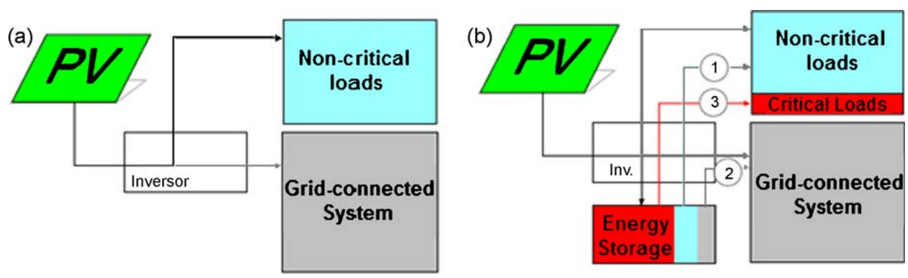


Fig. 10. Photovoltaic systems interconnected to the grid: (a) without energy storage, (b) utilizing energy storage with the following options (1) local load management, (2) load management for the utility, and (3) considering critical emergency loads.*Source*: [11].

lead–acid battery; (vii) unaffected by ambient temperatures (operates at 290–360 °C), capable of being installed in either protected or unprotected environments; (viii) allows for remote operation and monitoring with minimal maintenance; (ix) no emissions or vibrations, low noise compared to other energy conversion systems; and (x) 98% of the material utilized in the NaS batteries can be recycled, only sodium cannot be reused [26,27].

An electrical power system was used to obtain optimal integration of both central and distributed energy assets introducing distributed energy resources into the grid, thereby allowing unprecedented levels of control, utilization, efficiency, and reliability. The American Electric Power (AEP) utility company in the USA installed a 1.2 MW NaS-based distributed energy storage system at North Charleston, WV, the first in North America in June 2006. After 1-year of operation and testing, AEP has concluded that, although the initial costs of this system are greater than conventional power solutions, the system benefits justify the decision to create a distributed energy storage systems with intelligent monitoring, communications, and control for planning of the future grid. The results showed that the roundtrip AC energy efficiency of this energy storage system was measured at 76%. Energy cost saving was approximately $57,000 during the first 11 months of operation, if utilized at 100% of its capacity. This saving can be further increased if the utility makes the adjustment for a daily charge–discharge configuration to optimize energy arbitrage [28].

4. Distributed photovoltaic generation and energy storage system

4.1. Photovoltaic systems with energy storage systems

Photovoltaic generation alone, in function of its intermittence and operating period, generally does not significantly act on the energy demand balance at peak hours when connected to electrical energy systems [29]. An exception to this rule exists when the peak hours fall within the operation period of the energy source; for example, peak hours encountered during the day, in the case of air conditioning [21]. However, with increases in storage, energy can be managed, substantially increasing the aggregated value of photovoltaic systems.

According to Hoff et al. [10,11] and Perez et al. [12], when considering photovoltaic systems interconnected to the grid and those directly connected to the load demand, energy storage can add value to the system by: (i) allowing for load management, it maximizes reduction of consumer consumption from the utility when associated with a demand side control system; (ii) increasing the capacity of utilities to prevent energy interruptions when the photovoltaic system is available and generating electricity; and (iii) enabling consumers to support local critical loads and attend their own energy demands in the case of system failure, maintaining electrical service and increasing reliability of the system. Fig. 10 presents a schematic diagram of photovoltaic systems connected to the grid with and without energy storage systems, showing the undeniable increase in flexibility with the insertion of the energy storage system [11].

Photovoltaic systems with storage can therefore be utilized as dispatchable systems in accordance with the operational demands of the interconnected system, the utility or the consumer, adding a new dimension to energy usage.

4.2. Peak-shaving with photovoltaic systems and NaS battery storage

From the utility's point of view, the use of photovoltaic generation with energy storage systems adds value by allowing energy utilization during peak hours and by modeling the load curve. An example of this application can be seen in Fig. 9.

Energy storage and its utilization in the electrical grid add value to renewable energy sources such as solar energy, allowing for more intense use of these technologies. Its use includes applications in load leveling, peak-shaving, integration of renewable sources and energy trading, making the system more stable and reliable [30,31].

Photovoltaic panels with NaS battery storage systems applied for peak-shaving basically function in one of three operational modes [32]: (i) battery charging stage, when demand is low the photovoltaic system (more energy generated than consumed) or the electrical grid will charge the battery modules; (ii) battery system in standby, the photovoltaic systems attends demands (high) and is generating electricity; and (iii) battery discharge state, both batteries and photovoltaic panels meet peak demands (when during the day), or the batteries meet peak demands when photovoltaic energy is scarce and the marginal cost of energy provided by the utility is high.

5. Conclusion

Solar energy is applicable in nearly all circumstances due to its modularity, portability and simplicity of installation. It is a source of clean energy since generation, transformation and usage include no pollution generation. It has an extended useful life and permits energetic self-sufficiency without raw material costs.

The high cost of photovoltaic installation can be minimized with load management and energy storage systems. The photovoltaic system with a NaS battery storage system is an efficient method to add value and make its connection to the energy grid economically viable.

Sodium–sulfur battery technology is already well developed. It has a long useful life and high efficiency in relation to other batteries, requiring minimal space for installation. Its installation together with photovoltaic systems permits the installation of these systems in dense population areas, interconnected to buildings, which makes the system even more interesting since no transmission lines are necessary.

Application of photovoltaic systems with NaS batteries for peak-shaving is another tool that can be used by utilities to increase reliability of their systems and include the use of renewable energies.

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